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Spatiotemporal variation in vegetation spring phenology and its response to climate change in freshwater marshes of Northeast China

Xiangjin Shen [a,*], Binhui Liu [b], Zhenshan Xue [a], Ming Jiang [a], Xianguo Lu [a], Qing Zhang [c,*]

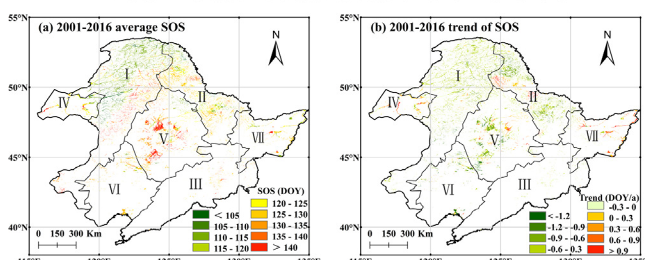
[a] Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, China
[b] College of Forestry, Northeast Forestry University, Harbin 150040, China
[c] LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

HIGHLIGHTS

- The start of the growing season (SOS) obviously advanced in most freshwater marshes.
- The effects of climate change on SOS are different among ecological function regions.
- Precipitation and temperature determines SOS in arid and cold regions, respectively.

GRAPHICAL ABSTRACT

Long-term averaged start date of vegetation growing season (SOS) and annual trend in SOS in freshwater marshes of Northeast China from 2001 to 2016



Ⅰ, Ⅱ, Ⅲ: mountain regions; Ⅳ, Ⅴ, Ⅵ: arid or semi-arid regions; Ⅶ: humid or sub-humid region

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ABSTRACT

Understanding wetland vegetation phenology and its response to climate change is important to predict the changes of wetland vegetation in wetland regions. Using the NDVI and climate data, this work studied the spatiotemporal change of start date of vegetation growing season (SOS) and explored the possible effects of climate change on the SOS over freshwater marshes of Northeast China. The results showed that the SOS significantly advanced by 0.52 day per year throughout the freshwater marshes of Northeast China during 2001 to 2016. The significant advancing of SOS was mainly concentrated in freshwater marshes of the Khingan Mountains (the Greater Khingan Mountains and the Lesser Khingan Mountains) and central arid or semi-arid regions (Songnen plain and Liaohe plain) in Northeast China. By contrast, there were weak delay trends of SOS in freshwater marshes of Eastern Inner Mongolia region, and Sanjiang plain. We found that precipitation was a dominant factor determining the SOS in arid or semi-arid regions (Songnen plain and Liaohe plain), while temperature played a bigger role in determining the SOS in Sanjiang plain and three cold mountains of the Northeast China. During the study period, increasing precipitation in the winter and spring contributed to advancing SOS in Songnen plain and Liaohe plain; the decrease of temperature from December to April explain the delaying SOS in freshwater marshes of Sanjiang Plain; the weak warming of temperature between November and May account for the advancing SOS of freshwater marshes in three cold mountains. In freshwater marshes of cold and the most arid region of Northeast China (Eastern Inner Mongolia), the SOS was influenced by both precipitation and temperature. Decreasing precipitation between January and April, as well as temperature decreases in March and April explain the delay of SOS in freshwater marshes of Eastern Inner Mongolia region.

* Corresponding authors.
E-mail addresses: shenxiangjin@iga.ac.cn (X. Shen), zhangqing@mail.iap.ac.cn (Q. Zhang).

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1. Introduction

Wetlands have a significant effect on the global carbon cycle and global climate change (Whiting and Chanton, 2001; Erwin, 2009; Hao et al., 2011; Mitsch et al., 2013). The phenology of wetland vegetation plays a key role in affecting the carbon cycle, energy exchange and ecosystem functions in wetland areas (Hess et al., 1995; Chmielewski and Rötzer, 2001; Jolly and Running, 2004; White and Lewis, 2011; Zhao et al., 2013a, 2013b; Calero et al., 2015). As the phenology of vegetation is very sensitive to the change of climate (Badeck et al., 2004; Menzel et al., 2006), investigating the responses of vegetation phenology to climate change is becoming a focus of global change research (Gordo and Sanz, 2010; Cong et al., 2012; Richardson et al., 2013; Piao et al., 2015; Shen et al., 2018a). Although there is a lot of research that has studied the effects of climate change on vegetation phenology in different regions of the world (Zhang et al., 2004; White et al., 2005; Peñuelas and Filella, 2009; Piao et al., 2011; Wu et al., 2015; Cong et al., 2017), very little research has explored the effects of climate change on wetland vegetation phenology. Compared to other ecosystems, wetland ecosystem has distinctive biological and non-biological conditions (Finlayson et al., 1999), which may lead to distinct responses of vegetation phenology to climate change. In the context of climate change, understanding the spatiotemporal variation in vegetation phenology and its response to climate change in wetland regions is important to predict the changes of regional wetland vegetation (Yan et al., 2015).

As a typical type of wetland, marshes are widely distributed throughout the world (Odum, 1988). The area of freshwater marshes in Northeast China is the largest in China, which accounts for about 48.3% of the freshwater marshes throughout China (Liu, 2005; Niu et al., 2009). Freshwater marshes in Northeast China are very important to regulate the regional climate and protect biodiversity of Northeast Asia (Ding et al., 2002; Song et al., 2008; Shen et al., 2018b). During the past decades, freshwater marshes of Northeast China have changed dramatically due to the effects of both human activities and climate change (Liu et al., 2013; Mao et al., 2014). Although some studies have investigated the effects of climate change on the distributions and vegetation coverage of freshwater marshes over Northeast China (Zhou et al., 2009; Wang et al., 2011; Mao et al., 2014; Shen et al., 2018b), little research has examined the dynamics of vegetation phenology and its response to climate change in freshwater marshes of this region. In the context of global climate change, exploring the effects of climate change on vegetation phenology of freshwater marshes in Northeast China can contribute to understanding the mechanism of the effects of climate change on wetland vegetation.

By using the normalized difference vegetation index (NDVI) dataset, this study analyzed the temporal and spatial changes of vegetation spring phenology over the freshwater marshes in Northeast China. In addition, based on the climate data, the relationships of spring phenology with temperature and precipitation were analyzed to reveal the possible effects of climate change on the variations of spring phenology. Considering the responses of vegetation to climate change may vary among different ecological function regions of Northeast China (Shen et al., 2018b), we compared the variation in vegetation spring phenology and its response to climate change at different ecological function regions of Northeast China. The aim of current work was to understand the spatiotemporal variation in vegetation spring phenology and its response to climate change, and to test if the effects of climate change on wetland phenology differ among ecological functional regions in freshwater marshes of Northeast China.

2. Materials and methods

2.1. Study area

The study area of this study is the Northeast China, which includes Eastern Inner Mongolia region, Heilongjiang, Jilin, and Liaoning Provinces. Based on the topography, climate and other natural conditions, the Northeast China includes seven ecological functional regions: Eastern Inner Mongolia region, Liaohe plain, Songnen plain, Sanjiang plain, the Changbai Mountains, the Lesser Khingan Mountains, and the Greater Khingan Mountains (Fig. 1). The topography of the Northeast China is characterized by three plains and three mountains. Three plains of Songnen plain, Liaohe plain, and Sanjiang plain are located in the central, southern and northeast parts of the Northeast China, respectively. Both the Liaohe plain and Songnen plain are surrounded by the Changbai Mountains in the east, the Lesser Khingan Mountains in the northeast, and the Greater Khingan Mountains in the west (Fig. 1). The climate in Northeast China is characterized by a relative long and cold winter (Shen et al., 2014). The areas of Eastern Inner Mongolia, Songnen Plain and Liaohe plain are regulated by arid or semi-arid climate (Table 1) (Zhang et al., 2014; Shen et al., 2018b), with the dominant vegetation of temperate steppe and semi-arid shrubs (Shen et al., 2018b). Due to high elevation, the temperature in Eastern Inner Mongolia is much colder than that in Songnen Plain and Liaohe plain (Table 1). By contrast, the climate of Sanjiang plain belongs to temperate humid or sub-humid monsoon climate, with wet hot summers and dry cold winters (Zhang et al., 2015). The main plants in freshwater marshes of Sanjiang plain contain *Phragmites communis*, Calamagrostis angustifolia, *Carex lasiocarpa*, Carex pseudocuraica, *Betula fruticosa*, *Carex meyeriana*, *Salix brachypoda*, and *Alnus sibirica* (Wang et al., 2011). The climate in the Changbai Mountains, the Lesser Khingan Mountains, and the Greater Khingan Mountains of is mountain climate. Due to high latitude, vegetations in freshwater marshes of three mountains include grasslands, shrubs, and cold-temperate coniferous forests (Xing et al., 2010; Tang et al., 2015; Wu et al., 2016; Fu et al., 2018).

2.2. Data

Data used in this study included monthly mean air temperature and total precipitation data during 2000 to 2016 for 90 meteorological stations throughout Northeast China (Fig. 1). These climate data were obtained from Chinese Meteorological Administration. A vigorous data assurance policy has been performed to guarantee the quality of these data (Shen et al., 2018b). In addition, we used the Moderate Resolution Imaging Spectrometer (MODIS) NDVI data during 2000 to 2016 in this study. These NDVI data has a spatial resolution of 250 m × 250 m and a temporal resolution of 16 day. Based on pixel reliability parameters, the initial quality control of these MODIS NDVI dataset have been made to minimize their errors and biases (Hwang et al., 2012). To get the unchanged freshwater marshes over Northeast China during the study period, two freshwater marshes maps for the year 2000 and 2015 covering the Northeast China were also used in this study. These two maps of freshwater marshes distribution were provided by Chinese Academy of Sciences, the accuracy of which has been evaluated based on field survey (Shen et al., 2018b).

2.3. Methods

The Polyfit-Maximum method (Piao et al., 2006) was used in this study to determine the SOS in freshwater marshes of Northeast China. The principle of Polyfit-Maximum method is setting the date of largest NDVI increase as the starting date of growing season. Because of its good performance, the Polyfit-Maximum method has been widely used in identifying the SOS over the world in recent years (Fu et al., 2014; Piao et al., 2015; Wang et al., 2016; Wang et al., 2017; Shen et al., 2018a). According to previous studies, 6-degree polynomial function was adopted to filter the NDVI time-series in obtaining the SOS in current study (Piao et al., 2006; Cong et al., 2012; Shen et al., 2018a). In order to avoid the impacts of land use/cover change on the results, this study only analyzed the unchanged freshwater marshes (pixels belonging to freshwater marshes in both the 2000 and 2015) during the study period. For each variable of this study, the regional mean value

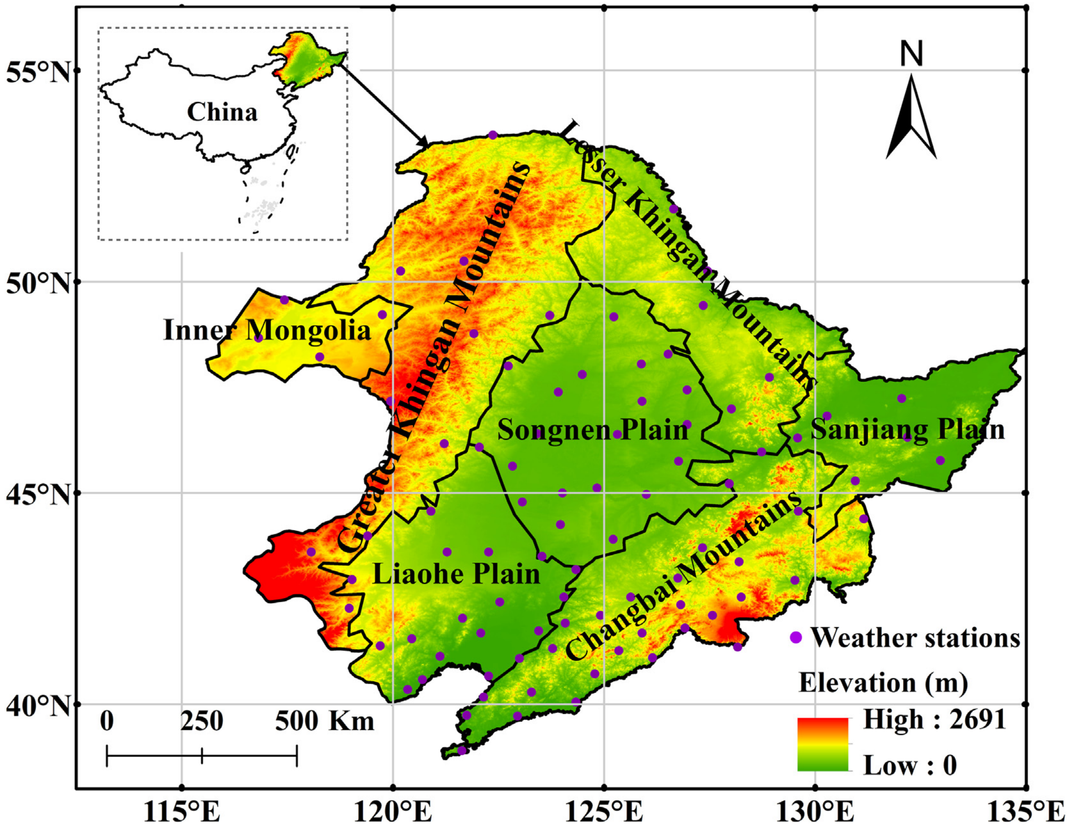

Fig. 1. The spatial distributions of seven ecological functional regions and 90 weather stations in Northeast China.

was calculated from the averages of all the pixels distributed in freshwater marshes of the ecological functional region (Shen et al., 2016). In addition, we used the simple linear regression to analyze the temporal trend in SOS during 2001 to 2016. For each pixel, the equation of simple linear regression is shown in Eq. (1):

$$SLOPE = \frac{n * \sum_{i=1}^{n} i * SOS_i - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} SOS_i\right)}{n * \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{1}$$

where *SLOPE* means the change trend of SOS, i indicates the ordinal number of the year, SOS_i is the SOS value for year i; and n is the number of analyzed years ($n = 16$ in current work), The positive or negative *SLOPE* value indicates delaying or advancing trend of SOS during the study period. The *SLOPE* value of zero indicates no detectable change in SOS during the study period. In this study, partial least-squares (PLS) regression (Wold, 1995) was used to investigate the effects of precipitation and temperature on the SOS. The correlation statistics of PLS regression is the canonical correlation analysis (Barker and Rayens, 2003). It is reported that the PLS regression can avoid the autocorrelations between independent variables (Yu et al., 2010), and thus it has been widely used in analyzing the relationships between the dependent and independent variables (Wold et al., 2001; Luedeling et al., 2013). To explore the effects of climate change on the SOS of freshwater marshes in Northeast China, this study analyzed the response of SOS to monthly total precipitation and mean temperature from July of the previous year to June of the same year, as calculated by PLS regression. For each independent variable, a value of variable importance in the projection (VIP) and a model coefficient (MC) were calculated in the PLS regression. Consistent with previous studies (Wold et al., 2001; Guo et al., 2015), variables with VIP ≥ 0.8 were considered important in the model of this study.

3. Results and discussions

3.1. Spatiotemporal change of vegetation spring phenology of freshwater marshes

Fig. 2 shows the spatial patterns of long-term averaged starting date of vegetation growing season (SOS) and the annual trend of SOS in freshwater marshes of Northeast China. Both the long-term averaged SOS and temporal trends in SOS have obvious spatial heterogeneities in the study area (Fig. 2). The results showed that the average SOS of freshwater marshes in Northeast China is primarily between 110 day of the year (DOY) and 150 DOY, which is generally consistent with the SOS results for vegetations across the Northeast China reported in previous studies (Fang and Fang, 2006; Gong and Chen, 2009; Zhao et al., 2013a, 2013b; Hou et al., 2014; Zhao et al., 2016). During 2001 to

Table 1
Annual average temperature (°C) and total precipitation (mm) for seven ecological regions in Northeast China during 2000–2016.

	Liaohe plain	Songnen plain	Eastern Inner Mongolia	Greater Khingan Mountains	Lesser Khingan Mountains	Changbai Mountains	Sanjiang plain
Annual average temperature	8.52	4.57	0.54	1.26	1.59	6.57	4.13
Annual total precipitation	529.78	461.73	265.11	469.47	550.85	739.87	535.45
Climate conditions	semi-arid climate	semi-arid climate	arid climate	mountain climate	mountain climate	mountain climate	temperate monsoon climate

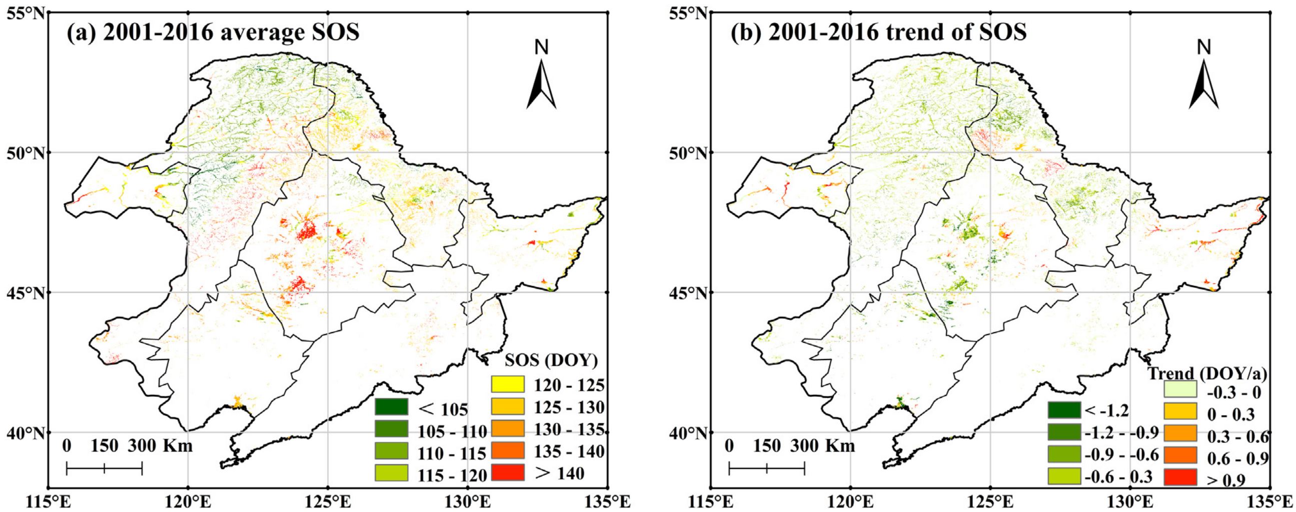

Fig. 2. Spatial patterns of long-term averaged start date of vegetation growing season (SOS) (a) and annual trend in SOS (b) in freshwater marshes of Northeast China from 2001 to 2016.

2016, the average SOS of freshwater marshes in Northeast China occurred on 125 DOY (corresponding to May 5, or May 4 in leap years). The earlier SOS is mainly seen in the north regions of the Greater Khingan Mountains, and later SOS is mainly distributed in Songnen Plain (Fig. 2a). The altitude of the greater Khingan mountains is much higher than that of the other mountain chains. Due to high latitude and altitude, the north regions of the Greater Khingan Mountains are the coldest regions of the Northeast China. In cold areas of the Greater Khingan Mountains, the vegetations spring phenology is more determined by the temperature. It is reported that vegetation in the regions that have a cold winter requires certain threshold of cumulative temperature for initiating green-up (Shen et al., 2011). Some studies found that the heat requirements decreased in cooler regions (Zhang et al., 2007; Liu et al., 2014). Therefore, the required cumulative temperature threshold for beginning the spring growth of vegetation in the Greater Khingan Mountains may be less than in other ecological functional regions of Northeast China, which possibly explains the earlier SOS in this region. In addition, we found that the spatial patterns of SOS were different among three mountains. For example, early SOS in high-altitude regions of the Greater Khingan mountains were not found in high-altitude regions of the Changbai Mountains (Fig. 2a). This phenomenon may be partly related to the effect of the "mountain mass elevation", which is important for determining weather patterns in mountainous regions. It is reported that, due to mass elevation effect, growing season is longer and warmer at any elevation in the interior mountains than in the outer mountain ranges (Grubb, 1971; Yao et al., 2015). However, further studies are still needed to explore the effects of "mountain mass elevation" on SOS in the mountains of Northeast China, although it is not the focus of current paper. In arid or semi-arid regions of Songnen plain and Eastern Inner Mongolia, most freshwater marshes are seasonal wetlands, which have a seasonal dry-wet alternation (Zheng et al., 2005). As the winter snow melts and spring precipitation increases, wetland vegetations in these arid regions start to grow at the beginning of the growing season. Therefore, in freshwater marshes of these arid or semi-arid regions, water condition is the limiting factor affecting the spring growth of vegetation (Shen et al., 2016, 2017). It is reported that temperate grasslands in China needs a certain amount of spring precipitation for triggering the spring green-up (Shen et al., 2018a). Under the conditions of arid or semi-arid climate, accumulating a certain amount of precipitation over relatively long time period may account for the later SOS in Songnen Plain. Although Eastern Inner Mongolia and Songnen plain are the two most arid regions of Northeast China (Table 1), the less heat requirements in Eastern Inner Mongolia due to cold environment may partly explain the relative early SOS in this region than in Songnen plain (Fig. 2a).

For the annual trends of SOS, we found a general advancing trend over the freshwater marshes of Northeast China during 2001–2016 (Fig. 2b). Over the study period of 2001 to 2016, the mean SOS throughout the freshwater marshes of Northeast China significantly advanced by 0.52 day per year (hereafter referred to as day/a) ($P = 0.01$). For different ecological functional regions, the mean SOS also showed a significant advancing trend in freshwater marshes of Liaohe plain (0.73 day/a; $P = 0.00$), Songnen plain (0.39 day/a; $P = 0.02$), the Greater Khingan Mountains (0.47 day/a; $P = 0.04$), and the Lesser Khingan Mountains (0.58 day/a; $P = 0.02$) (Fig. 3). By contrast, the SOS advanced at a rate of 0.32 day/a in freshwater marshes of Changbai Mountains, but it was not significant ($P = 0.20$). In addition, there were weak delay trends of SOS in freshwater marshes of Eastern Inner Mongolia region (0.12 day/a; $P = 0.64$), and Sanjiang plain (0.19 day/a; $P = 0.58$). These different changes of SOS in seven ecological functional regions may be related to the different climate changes and different effects of climate change on vegetation growth in these regions (Shen et al., 2018b).

3.2. The effects of climate change on SOS

For climate changes in freshwater marshes of Northeast China during 2000 to 2016, we found that monthly total precipitation showed different changes among ecological function regions (Table 2). In terms of temperature changes, temperatures through December to May showed no significant changes in all ecological function regions (Table 3). The VIP results showed that the significant effects of precipitation and temperature on the SOS were mainly concentrated between November and May (VIP values above 0.8). The negative model coefficients (MC) in these months suggest that increasing precipitation and warm temperatures could advance the SOS over the freshwater marshes of Northeast China. However, the roles of precipitation and temperature in influencing SOS were different among seven ecological function regions (Figs. 4, 5). In general, precipitation was a dominant factor determining the SOS in arid or semi-arid areas of Songnen plain and Liaohe plain, while temperature played a more important role in affecting the SOS in Sanjiang plain and three mountains of the Changbai Mountains, the Lesser Khingan Mountains and the Greater Khingan Mountains. In Eastern Inner Mongolia region, the SOS was influenced by both precipitation and temperature. The different natural environments in these ecological function regions seem to account for this phenomenon.

Under the global warming background, it is reported the dependence of vegetation growth on temperature decreased in Northeast China (Wei et al., 2017). Many studies have highlighted the hydrological regulation of vegetation growth in a warmer climate of Northeast China,

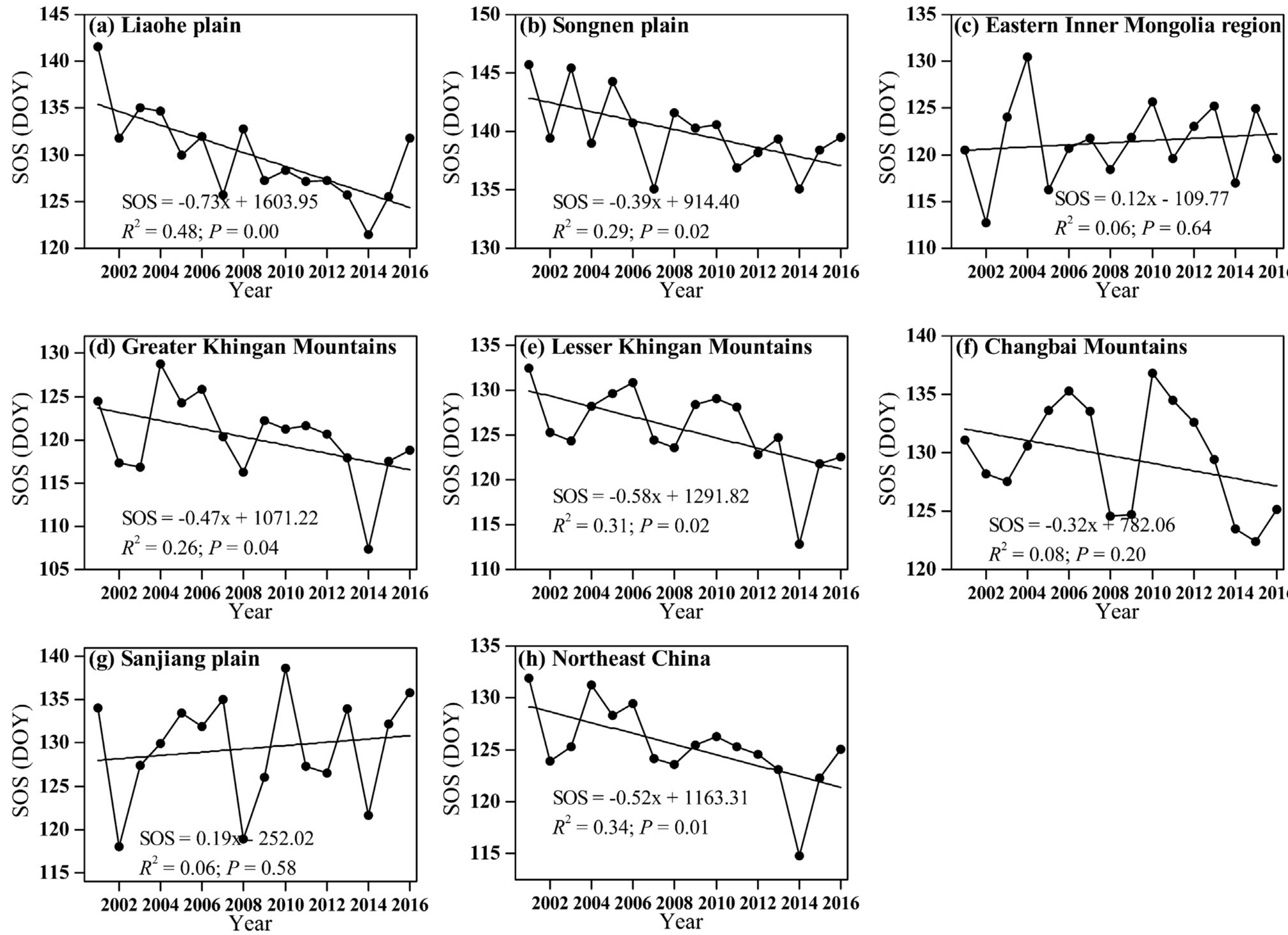

Fig. 3. Temporal changes in start date of vegetation growing season (SOS) for freshwater marshes in Northeast China during 2001 to 2016.

even in wetland environments (Wei et al., 2017; Shen et al., 2018b). In arid or semi-arid areas of Northeast China, the changes in vegetation growth were not determined by temperature or solar radiation, but were more regulated by the soil moisture content and drought (Shen et al., 2013). Shen et al. (2018b) found that, due to high soil moisture content and reduced drought, increasing precipitation could promote the growth of vegetation in freshwater marshes of arid or semi-arid regions in Northeast China. For Liaohe plain, large VIP values (>0.8) and negative MC indicate that more precipitation during the winter (December to February) and spring (March through May) had a significant advancing impact on the SOS of freshwater marshes in this region (Fig. 4). Based on the change trends of precipitation (Table 2), we can conclude that increases of precipitation during the winter and spring account for advancing SOS in freshwater marshes of Liaohe plain. Although increasing precipitation during winter and spring also seems to advance SOS in freshwater marshes of Songnen plain, the significant effect of precipitation was only found in February and May (Fig. 4). It is interesting that the significant increase of precipitation were only found in these two months (Table 2). It suggests that precipitation change may not have no-significant impact on the SOS until it reached a certain level. In terms of temperature effects, we found no-significant impacts of temperature on SOS in these two regions (Fig. 5a, b). The moderate VIP values and positive model coefficients suggest that warming spring temperature might even delay the SOS in freshwater marshes of these two arid or semi-arid regions. This is because that warm spring temperature could decrease water availability and exacerbate drought effects

Table 2
Rates of change in monthly total precipitation (mm/decade) for freshwater marshes in Northeast China during 2000–2016. *$P < 0.05$; **$P < 0.01$.

Different months	Liaohe plain	Songnen plain	Eastern Inner Mongolia	Greater Khingan Mountains	Lesser Khingan Mountains	Changbai Mountains	Sanjiang plain	Northeast China
June	13.56	31.54	21.08	29.89	40.00	19.01	19.89	23.72
July	15.59	15.06	22.40	29.03	8.92	−7.86	18.54	9.98
August	−15.27	5.79	15.83	21.87	−1.95	32.16	−4.85	10.96
September	12.36*	21.54	4.85	14.53	20.81	0.99	23.08	12.28
October	2.60	4.11	2.91	−0.57	3.16	0.92	−1.78	1.85
November	43.32	2.94	2.51	2.06	4.44	17.33*	12.26	15.04**
December	32.53	3.60	1.36	0.94	5.76*	1.32	11.60*	8.34
January	32.13	−2.00	−1.88	−1.60	−2.84	−4.01*	−3.63	3.35
February	3.93*	4.41*	−0.42	0.57	3.84	6.00	−0.08	3.82
March	0.42	2.31	−1.03	−0.92	−1.57	−0.73	−6.36	−0.28
April	7.94	−10.26	−2.63	0.80	−13.69*	0.58	−4.79	−2.07
May	29.26*	38.41**	7.78	16.98*	19.47	22.26	31.88	26.50*

Table 3
Rates of change in monthly mean temperature (°C/decade) in freshwater marshes of Northeast China from 2000 to 2016. *$P < 0.05$; **$P < 0.01$.

Different months	Liaohe plain	Songnen plain	Eastern Inner Mongolia	Greater Khingan Mountains	Lesser Khingan Mountains	Changbai Mountains	Sanjiang plain	Northeast China
June	−0.91	−0.26	−1.36	−0.45	0.50	−0.60	0.35	−0.46
July	−0.64	−0.32	−0.71	−0.28	0.07	−0.11	0.14	−0.27
August	0.17	0.19	−1.13	0.19	0.46	0.10	0.47	0.14
September	−0.79*	−0.84*	−1.20	−0.56	−0.40	−0.34	−0.34	−0.60
October	0.34	0.35	0.50	0.81	0.32	0.32	0.14	0.38
November	0.63	1.44	0.72	1.31	1.76	0.98	1.41	1.13
December	0.48	0.51	0.52	1.20	0.83	0.16	−0.05	0.46
January	−0.45	−0.66	−1.65	−0.52	−1.22	−0.13	−0.87	−0.57
February	−0.79	−0.63	−0.95	−0.78	−1.16	−0.79	−0.93	−0.76
March	0.22	−0.28	−0.27	0.27	−0.65	0.12	−0.16	−0.01
April	−0.60	−0.29	−0.44	0.23	−0.13	−0.51	−0.40	−0.41
May	−0.27	−0.42	0.12	0.38	0.25	0.15	−0.51	−0.16

(Shen et al., 2018a), thereby delaying the onset of green-up in these arid regions. For freshwater marshes of Eastern Inner Mongolia region, we found that apart from precipitation, the temperature change could also affect the SOS in this region. The results of PLS regression showed that precipitation between January and April, and temperatures in March and April had significant effects on SOS change in freshwater marshes of Eastern Inner Mongolia region (VIP values above 0.8) (Fig. 5). Compared with the other two arid or semi-arid regions, Eastern Inner Mongolia region has higher elevation and lower temperature. Thus it becomes reasonable that the SOS in this cold and arid region is regulated by both temperature and precipitation. Based on the changes of precipitation and temperature (Tables 2, 3), we can conclude that decreasing precipitation between January and April, as well as temperature decreases in March and April explain the delay of SOS in freshwater marshes of Eastern Inner Mongolia region.

In this study, we found that the SOS was determined by temperature in freshwater marshes of Sanjiang plain, and the three mountains (the Changbai Mountains, Lesser Khingan Mountains, the Greater Khingan

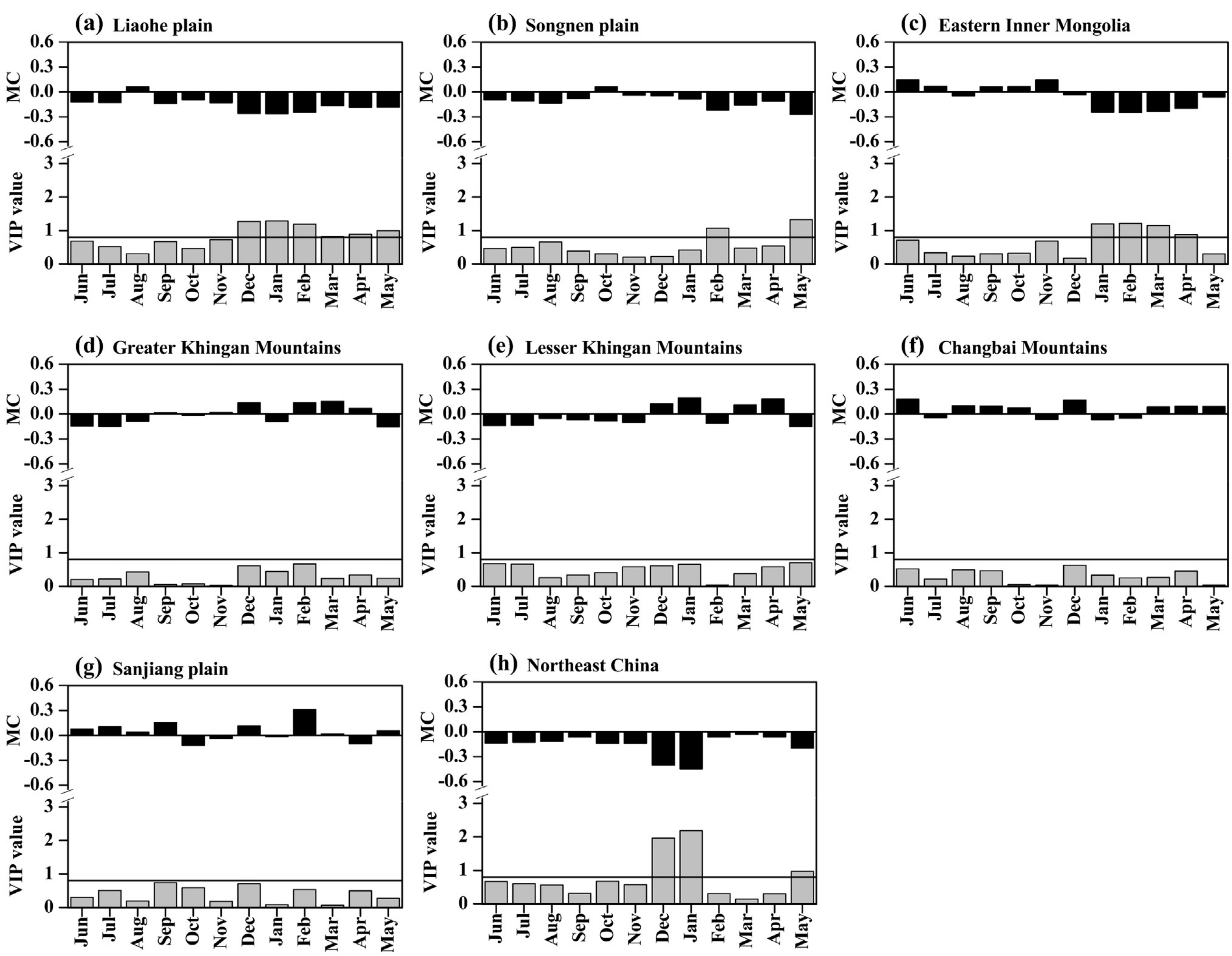

Fig. 4. Responses of start date of vegetation growing season (SOS) in freshwater marshes of Northeast China to 2001–2016 change of monthly total precipitation based on partial least-squares (PLS) regression. The variable importance plots (VIP) values and model coefficients (MC) show the significance and degree of the effect of precipitation on the SOS, respectively.

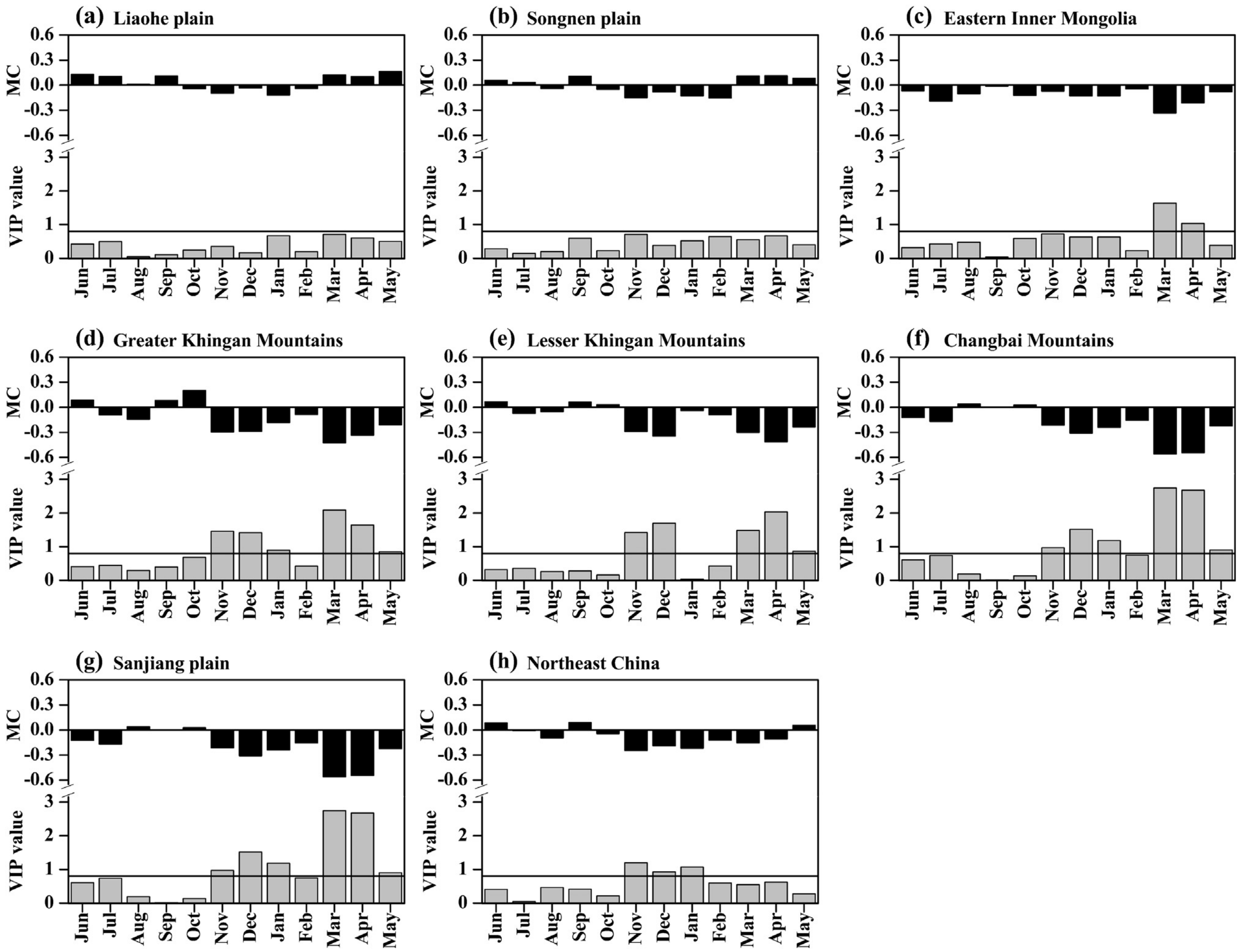

Fig. 5. Responses of start date of vegetation growing season (SOS) in freshwater marshes of Northeast China to 2001–2016 change of monthly mean temperatures based on partial least-squares (PLS) regression. The variable importance plots (VIP) values and model coefficients (MC) show the significance and degree of the effect of temperature on the SOS, respectively.

Mountains). In freshwater marshes of Sanjiang plain, the VIP values and MC showed that warm temperatures through December to April had a significant effect advancing the SOS (Fig. 5). The significant effects of temperature during winter and spring may be related to certain heat accumulation for initiating green-up in relative cold region (Shen et al., 2011; Piao et al., 2015). Therefore, the decreasing temperature from December to April (Table 3) could explain the delaying SOS in freshwater marshes of Sanjiang Plain. Compared with arid or semi-arid areas of Northeast China, there are adequate water resources in Sanjiang Plain (Shen et al., 2018b). This may partly account for the fact that precipitation change did not have obvious effects on SOS in this region. In freshwater marshes of three mountains, the significant effects of temperature on SOS were concentrated between November and May, although with no significant effects of temperature in some above months (Fig. 5). The negative MC values from November to May indicate that warming temperatures in the winter and spring generally had an advancing effect on the SOS. The no-significant impacts of temperature on the SOS were found in January and February for the Lesser Khingan Mountains, and in February for the Greater Khingan Mountains and the Changbai Mountains. It is interesting that the largest decreases of temperature were found in January and February for the Lesser Khingan Mountains, and in February for the other two Mountains (Table 3). It is reported that vegetation in cold regions needs a certain heat accumulation above some threshold to trigger the spring green-up (Shen et al., 2011; Piao et al., 2015). During the cold winter, the declining temperature is more likely to be below the temperature threshold than warming temperature, thereby contributing less to fulfill the heat requirement for spring green-up. Therefore, the responses of SOS to decreasing winter temperature may become less sensitive in these cold mountains, which results in the no-significant effects of cooling temperatures in winter. This further confirms the findings of some previous studies about the asymmetric responses of SOS to warming and cooling temperatures (Signarbieux et al., 2017). Therefore, the weak warming of temperature in some months between November and May largely account for the advancing SOS of freshwater marshes in these three mountains. However, future research is still to investigate the influence of temperature on SOS in freshwater marshes of three mountains of the Changbai Mountains, Lesser Khingan Mountains, and the Greater Khingan Mountains. It is predicted that climate is becoming warmer and drier in Eastern Inner Mongolia, Songnen Plain and the Greater Khingan Mountains, but becoming warmer and wetter in the Changbai Mountains and Sanjiang Plain in the future (Gao et al., 2016; Chu et al., 2017). By contrast, there are increasing temperatures and no significant changes of precipitation in Liaohe Plain and the Lesser Khingan Mountains (Yin et al., 2001). Based on the advancing effects of warming temperatures on SOS in Sanjiang Plain and three mountains, we can predict earlier SOS of marshes in these regions. According to the impacts of precipitation on SOS, however, later SOS is predicted in Songnen Plain due to the effects of drought and decreasing soil moisture content caused by declining precipitation in this arid region.

It should be noted that there may exist some limitations in current study. The SOS results calculated from remote sensing data could contain some uncertainties due to the inaccuracy of satellite data (Shen et al., 2018a). In addition to the SOS, the length of the growing season

should also be investigated to further use the data effectively in the management of marsh vegetation under future climate change (Weiher and Keddy, 1995; Gong et al., 2015). Although the NDVI data have been widely used in obtaining vegetation phenology, the applications of NDVI data may have some limitations due to its sensitivity to soil background and its saturation in high vegetation coverage area (Huete et al., 2002). In addition, the medium resolution of MODIS NDVI data may affect the accuracy of the SOS results in this study. Some studies found that enhanced vegetation index (EVI) has optimized vegetation signals, and the reconstructed EVI time series could improve the calculation of vegetation phenology (Cao et al., 2015). Considering the uncertainties in remote-sensing estimates of vegetation phenology, future studies using the EVI data and higher-resolution images, as well as phenological data from in situ observations are still needed to verify the SOS results for freshwater marshes of Northeast China in current study.

4. Conclusions

Using the NDVI and climate data, this study analyzed the spatiotemporal change of SOS and possible effects of climate change on the SOS in freshwater marshes of Northeast China. During 2001 to 2016, the average SOS of freshwater marshes in Northeast China occurred on 125 DOY. The earlier SOS is mainly seen in the north regions of the Greater Khingan Mountains, while later SOS is mainly distributed in Songnen Plain. Throughout the freshwater marshes of Northeast China, the mean SOS significantly advanced by 0.52 day/a during the study period. The significant advancing of SOS was mainly concentrated in freshwater marshes of Songnen plain, Liaohe plain, the Greater Khingan Mountains, and the Lesser Khingan Mountains. By contrast, there were weak delay trends of SOS in freshwater marshes of Eastern Inner Mongolia region and Sanjiang plain.

The effects of temperature and precipitation 2001–2016 change on the SOS of freshwater marshes were different among ecological function regions in Northeast China. In general, precipitation was a dominant factor affecting the SOS in arid or semi-arid areas of Liaohe plain and Songnen plain, while temperature played a more important role in determining the SOS in Sanjiang plain and three cold mountains. In freshwater marshes of Eastern Inner Mongolia region, however, the SOS was influenced by both precipitation and temperature. During 2000 to 2016, increases in precipitation during the winter and spring contributed to advancing SOS in freshwater marshes of Liaohe plain and Songnen plain; the decrease of temperature from December to April contribute to the delaying SOS in freshwater marshes of Sanjiang Plain; the weak warming of temperature between November and May account for the advancing SOS of freshwater marshes in three cold mountains; decreasing precipitation between January and April, as well as temperature decreases in March and April explain the delay of SOS in freshwater marshes of Eastern Inner Mongolia region.

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